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14. ABSTRACT

Combining global and local measurements at multiple physical scales was demonstrated to provide a physically based framework to estimate the location, severity and type of damage in composite airframe structures. Unique spectral signatures of fiber Bragg grating sensors were correlated to individual failure modes of representative composite laminates. A combined experimental/numerical formulation for the optimization of sensor placement for an embedded sensor network was then developed based on a cost function of component lifetime. The cost incorporated both the increase in lifetime through the identification of damage modes through the sensor responses and the decrease in lifetime through the host-sensor interactions. The optimization methodology was based on a combined theoretical/experimental approach incorporating both the experimentally driven characterization of the role of embedded sensors on the component lifetime and computational modeling of damage mechanisms and sensor-host interactions within the composite material. The optimization procedure, as a function of embedded sensor density, revealed regions where the component lifetime was increased and decreased. A specialized finite element formulation was then derived and implemented to predict the

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Background

Damage identification and mitigation in composite aerospace structures is especially challenging due to the multiple, interacting failure modes present in the heterogeneous host material; sensor-host material interactions; and complicated remaining lifetime prediction strategies. *The goal of this project was to use internal strain measurements at multiple physical and time scales to improve in-service lifetime predictions of aerospace structures and the resulting structural components lifetime through condition based monitoring.* Embedding fiber Bragg grating (FBG) sensors within these composite structures allows one to correlate sensor response features to "critical damage events" within the material. The unique capabilities of this identification strategy are due to the detailed information obtained from the FBG sensors and the placement of the sensors within the interior of the laminate, that is, closer to the location of the failure modes. Further, the spectral characteristics of FBG sensors relate to damage states not merely strain amplitudes. The research objectives of this project were therefore to:

- demonstrate FBG sensor data acquisition and fusion at multiple temporal and physical scales;
- design and implement algorithms for the optimal distribution of embedded FBG sensors in airframe structures for in-situ failure identification;
- formulate a combined experimental-numerical formulation to incorporate sensor-host interaction into this optimization strategy.

In order to achieve these objectives, several technical challenges in the state-of-the-art needed to be overcome. The major two limitations were that current optimization strategies for sensor networks were limited to surface mounted sensor applications due to the increased complexity of embedded sensor interactions with the host material and that the acquisition of high speed FBG sensor data was limited to peak wavelength information.

Major Accomplishments

- Combining global and local measurements at multiple physical scales along with visual observations was demonstrated to provide a physically based framework to estimate *location, severity* and *type* of damage in composite airframe structures. Unique spectral signatures of FBG sensors were correlated to individual failure modes of representative composite laminates.
- Full spectral interrogation of embedded fiber Bragg grating sensors at 100 – 300 kHz was experimentally demonstrated during low-velocity impact loading of representative composite laminates. This increase in interrogation rate of multiple orders of magnitude permitted the expansion of the physically based framework to multiple time and physical scales for further refinement of the damage estimation.
- An experimental protocol was derived and demonstrated for representative laminated plates to quantify the host-sensor interaction and its effect on the laminate lifetime when subjected to multiple low-velocity impact events. Statistical distributions in total energy dissipated by the laminated plates (a measure of laminate lifetime) and total maximum contact force (a measure of laminate stiffness) were empirically collected for the representative material system.
- A combined experimental/numerical formulation for the optimization of sensor placement for a sensor network embedded in a composite airframe structure was developed based on a cost function of lifetime benefit. The lifetime benefit incorporated both the positive increase in

lifetime through the identification of damage modes through the combined sensor responses and the negative decrease in lifetime through the host-sensor interactions.

- A unit cell model was derived and demonstrated for the computational analyses of the sensor-host interaction to be used in future Monte Carlo analyses for further verification of the sensor placement optimization code. The use of the Transformation Field Analysis provided a unique predictive capability to uniquely correlate the sensor responses to failure mechanisms within the woven architecture of the representative material system.

- A specialized finite element formulation was derived and implemented to predict how the electrical-mechanical-thermal behavior of carbon nanotube (CNT) reinforced polymer composites is affected by electron tunneling distances, volume fraction, and physically realistic tube aspect ratios. Scaling relations were then developed to obtain gauge factors for different CNT arrangements within a polymer composite to ascertain piezo-resistive behavior for different CNT distributions and arrangements.

In-situ Impact-induced Damage Assessment of Woven Composite Laminates through a Fiber Bragg Grating Sensor Network

The prediction and assessment of impact induced failures in woven composites are challenging, due to multiple and simultaneous interacting failure mechanisms. However, the fusion of global measurements of contact force and energy dissipation with local measurements of post-impact residual strain and time-dependent strain relaxation can provide new insights into the multiple failure mechanisms associated with woven material systems. Woven composite specimens without sensor networks were subjected to multiple low velocity impacts to provide a benchmark on the global parameters of maximum contact force and dissipated energy. Critical damage events and indicators were identified for each specimen based on these global measurements. Woven composite specimens with embedded sensor networks were impact tested while both global and local residual post-impact strain values were measured. Critical damage events were identified from post-mortem dissipated energy data for the specimens.

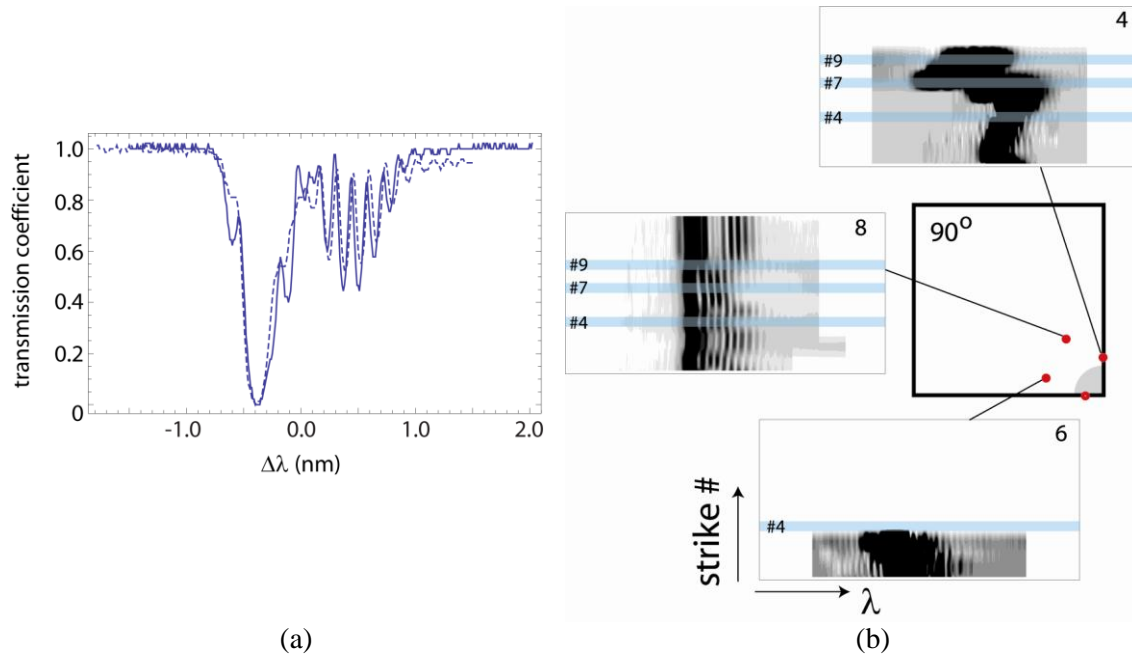(a)   (b)

Figure 1. (a) FBG spectra obtained in transmission. Spectrum prior to first impact is plotted as dashed line. Spectrum measured after strike 7 is plotted as solid line. All spectra have been normalized to account for coupling losses. (b) Spectral maps for sensors embedded in a composite laminate. Each horizontal slice is a grayscale map of intensity per wavelength after a particular strike. The vertical axes represent increasing strike numbers. The location of each sensor is also shown in inset.

For the tested woven composite specimens, using identical material systems and processes, there was a high variability in global parameters measured including number of strikes to failure, cumulative dissipated energy, and maximum contact force. Due to the complex woven geometry and therefore multi-axial, non-uniform local loading conditions on the embedded sensors, the average residual strain measured by the embedded FBG sensors did not correlate with the critical damage events, and was therefore an unreliable indicator of the extent of damage internal to the composite. The post-fabrication embedded signal was not as repeatable for woven composites as for laminates with uni-directional laminae, resulting in a large number of possible initial conditions prior to impact. The signatures of spectral broadening in the full spectral information from the FBG sensors, on the other hand, corresponded uniquely to these critical

damage events identified from the global parameters. A representative spectral after signal distortion is shown in Figure 1(a). The full spectral scans at lower data acquisition rates provided more useful damage information than rapid scans of the FBG network to identify the peak wavelengths (and average strains) for each sensor.

For the sensors that measured a significant change due to the damage growth before failure of the specimen, a rapid change in the spectral distribution occurred. This change included a broadening of the spectrum which may or may not have been accompanied by a significant shift to upper or lower wavelengths of the spectrum. This broadening of the spectrum corresponded to critical strike numbers previously identified post-mortem from the global measurements. This was not the case for the average residual strain data. Additionally, a significant shift in the average strain sometimes occurred without the formation of critical damage. This critical damage was thus better observed through the broadening of the spectrum. We therefore created the concept of a damage map based on the spectral distribution for each sensor. An example damage map is shown in Figure 1(b). It was shown that this measure correlates directly to the critical damage events previously identified from the global measurements and is therefore suitable as a critical damage indicator.

Full-spectrum Interrogation of Fiber Bragg Grating Sensors for Dynamic Measurements in Composite Laminates

In collaboration with researchers in the Department of Electrical and Computer Engineering at Brigham Young University, we designed, implemented and tested a full-spectral interrogator for fiber Bragg grating sensors that performed full-spectral sweeps at rates up to 1 kHz. This interrogator was later further developed and demonstrated through a separate National Science Foundation project to increase the full-spectral sweep rate to 100 kHz. We then demonstrated the dynamic full-spectral interrogation of a FBG sensor during low-velocity impact testing of a composite laminate. The sensor was embedded in a woven, representative aerospace composite laminate that was subjected to multiple low-velocity impacts. Observed transient spectral features included peak splitting, wide spectral broadening and a strong single peak at the end of the impact event (see Figure 2). Such features could not be measured through conventional peak wavelength interrogation of the FBG sensor. Cross-correlation of the measured spectra with the original embedded FBG spectrum (before embedment in the laminate) permitted rapid visualization of average strains and the presence of transverse compressive strain on the optical fiber. Combining peak wavelength scanning using a commercial, high speed interrogator (up to 625 kHz) with the full-spectral sweeps (albeit at lower scanning rates) yielded a powerful tool for the identification of material damage and failure modes in the composite laminates based on the response of FBG sensors near damage sites.

The measurement of unique, time dependent spectral features from the FBG sensor permitted the classification of the laminate lifetime into five regimes. In regime 1, the laminate responded to the impact event with a high stiffness. The sensor experienced compressive axial strain during the impact as the sensor was slightly above the neutral axis. However, as the neutral axis passed the sensor, the maximum axial strain decreased, eventually becoming tensile. Regime 2 was defined to begin when the neutral axis shifted above the sensor. Low levels of this transverse compression were also observed in the residual strain state between impact events due to permanent deformation in the laminate that was not released after the impact loading. In regime 3, the extent of damage had reached the location of the sensor. This observation was supported by the high levels of residual transverse compression on the sensor in between impact events and the temporary release of the sensor during loading. In regime 4 this residual transverse compression dominated the response of the FBG in the equilibrium state. The final regime was characterized by further fracturing of plies and an increase in relaxation time.
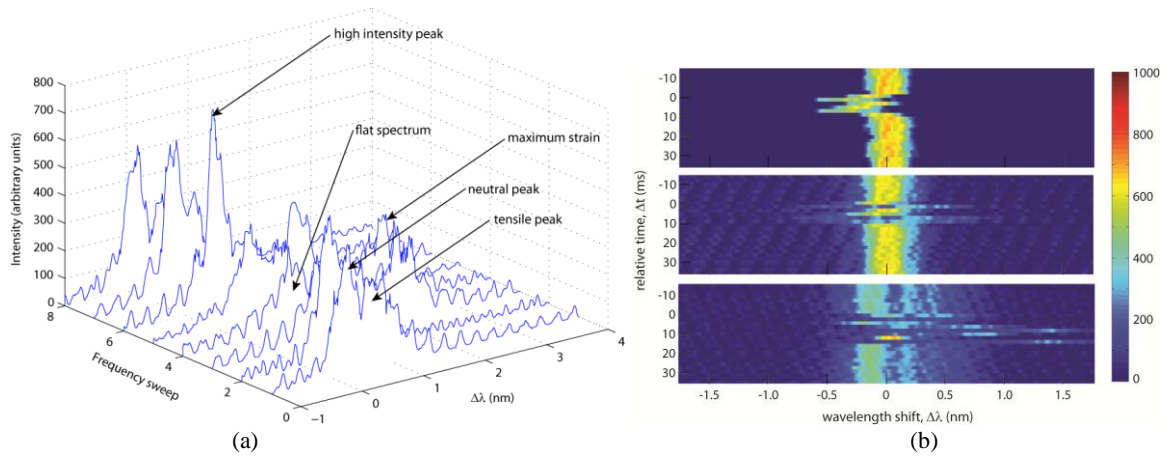
Figure 2: FBG intensity spectra obtained from consecutive frequency sweeps during a single impact event. Sweep 2 was recorded at the beginning of the impact response. (b) FBG intensity (arbitrary units) spectra obtained from strikes 6, 15 and 68 (top to bottom) from a single specimen. The intensity data for all strikes are normalized to the same maximum. Relative time refers to beginning of impact event.

These damage regimes compared well with previous analyses of the same material system using combined global and local FBG sensor information. These damage regimes could be identified strictly from the FBG full-spectral response without the need for information on the loading conditions and global response of the laminate. These measurements also demonstrated the richness of information that can be obtained from full-spectral interrogation of FBG sensors in a complex, multiple-stress-component environment.

Quantification of Probabilistic Representation of Host-Sensor Interaction for Impact Studies of Laminated Composites

Graphite fiber/epoxy, two-dimensional woven composite laminates were fabricated with various densities of embedded optical fibers at the midplane. The specimens were subjected to multiple low-velocity impacts until failure. The energy dissipated by the laminate and the maximum contact force were each measured for every impact event. Cumulative probability distributions were calculated for each embedded optical fiber density from which probability distribution functions in terms of embedded optical fiber density were extrapolated.

A significant barrier exists to extrapolate these observations of a single embedded optical fiber to a quantitative model of the role of embedded optical fiber density on the damage initiation and propagation in laminates due to low-velocity impact loading.[1,2] The extremely localized nature of failure initiation creates a large variability in the measured lifetime of identical specimens without embedded optical fibers. Furthermore, once embedded sensors are added to the laminate, these localized failures are highly sensitive to the local material geometry surrounding the optical fiber and the optical fiber placement itself.[3] A deterministic sensor-host interaction model can therefore not be realistically applied to predict the effects of the sensor on the host material lifetime.

The testing protocol yielded a good probabilistic representation of the laminate lifetime in terms of the accumulated dissipated energy at failure. The mean and standard deviation values of the different specimen groups are shown in Figure 3(a). The laminate lifetime was well represented by a normal distribution in terms of accumulated dissipated energy at failure. As expected, the mean laminate lifetime decreased with the optical fiber spacing, however there was also an optical fiber spacing threshold beyond which the laminate failure was dominated by the

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presence of the optical fibers and was not sensitive to the number of optical fibers. The extrapolated predictive dissipated energy at failure model is shown in Figure 3(b). The standard deviation of the laminate lifetime decreased with the number of optical fibers, confirming that the failure at higher spacing values was dominated by the presence of the optical fibers. While the resulting numerical values of the model would be different for another material system or impact loading history, the goal of this study is to derive the testing protocol and data analysis method to apply to any laminate configuration.

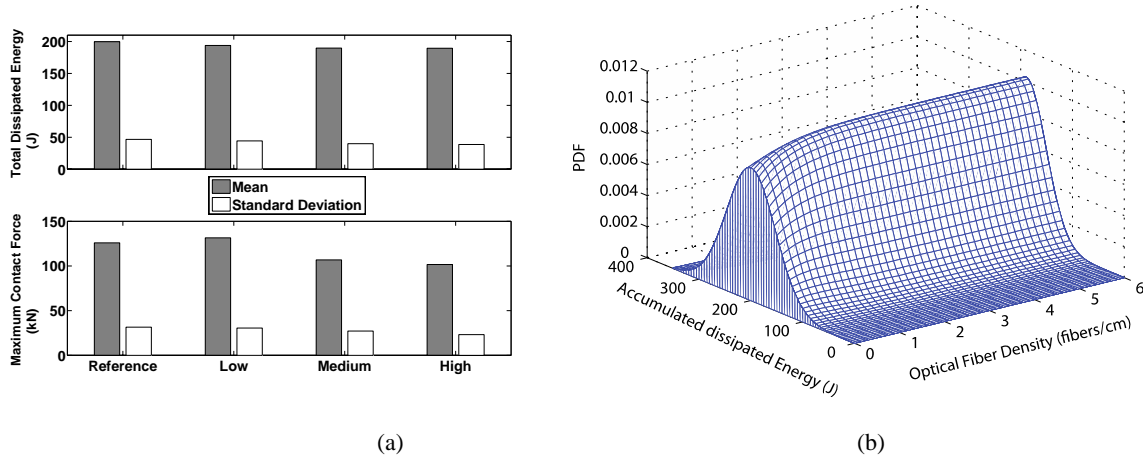(a)   (b)

Figure 3. (a) Mean and standard deviation values for total dissipated energy and maximum contact force for all specimen groups. (b) Probability distribution function for dissipated energy as a function of optical fiber density obtained from experimentally measured distributions.

Definition of High Performance Damage Measures Based on Fiber Bragg Grating Spectra

We derived and tested four different damage measures to rapidly process the full-spectral response of FBG sensors for the detection and quantification of the "extent" of damage. These damage measures later served as the signal processing portion of the sensor response model in the sensor placement optimization method described later. When applied near regions of strain concentrations or damage in a material, the reflected FBG spectrum often shows significant distortion,[4-6] as demonstrated in the earlier topics. This distortion is due to strain gradients, multiple strain components or non-uniformities or discontinuities in the strain field along the FBG axis and is theoretically predictable when the specific strain state is known (see Figure 4). When a detailed analysis is required, the distorted FBG reflected spectrum could be fit to known strain states[7,8] or an inverse optimization algorithm to invert the applied strain field from the spectrum.[9] However, these detailed analyses are obtained at the cost of high computational efforts and cannot necessarily be applied in real-time.

As demonstrated earlier, the exact damage state in the material is not deterministic. Therefore a successful quantitative damage measure must be robust to multiple sources of spectral distortion occurring simultaneously. Additionally, the measure must be insensitive to uniform applied strain (dominated by the magnitude of the loading applied to the structure and not uniquely sensitive to the presence of damage), power losses due to compression of the optical fiber at locations other than the FBG sensor (particularly prevalent for sensors embedded in material systems), and temperature fluctuations.

The damage measures derived and tested were the spectral bandwidth, number of peaks, cross-correlation coefficient with the undistorted spectrum and fractal dimension. Each damage measure was evaluated for two conditions: simulated FBG data that included only distortion due

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to a pure strain gradient and experimental data from multiple sensors embedded in a single laminate. The experimental data included complex strain fields, as well as measurement noise and realistic variations in sensor responses, representing a complex, realistic strain environment. The four damage measures tested did not necessarily behave the same for the simulated and experimental data. Some of these differences were due to the strong influence of the localized material microstructure and damage states on the embedded FBG spectral response. For this reason, testing the damage measures on actual experimental data from the same specimen was critical to understanding their behavior.
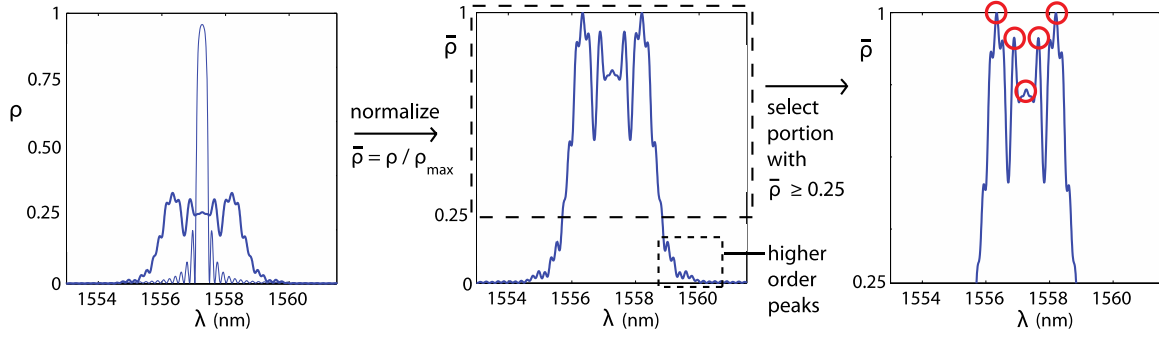

Figure 4. Schematic of calculation method for number of peaks damage measured for FBG reflected spectrum. Graph on left shows original spectrum (thin line) and distorted spectrum (thick line). The peaks identified in the final spectrum for this example are circled.

The best strategy in applying a damage measure would be to fuse the results of the spectral bandwidth and fractal dimension damage measures to incorporate the strengths of each approach: the low sensitivity to noise and high sensitivity to rapidly increasing strain fields of the spectral bandwidth and the high sensitivity to gradually changing strain fields of the fractal dimension. This need to fuse multiple criteria was consistent with previous experimental measurements, from which it was clear that interpretation of data from embedded FBG sensors represents a significant challenge for robustness. The cross-correlation coefficient had a high sensitivity to measure noise that could not easily be removed from the output. Improving the models of strain transfer between the surrounding material systems and the FBG sensors could permit a better correlation between spectral wavelength shifts. However such models would need to incorporate the statistical distribution of the localized variations in the material microstructure that affects both the FBG embedment and the damage accumulation. Tools for these models developed during this project are described in a later section.

Optimization of Embedded Sensor Placement for Structural Health Monitoring of Composite Airframes

We formulated an optimization method specifically for embedded sensors for structural health monitoring of composite airframe structures. The chosen cost function was the component lifetime, balancing both the positive benefits of the condition-based monitoring enabled by the sensor information with the negative costs of the structural-performance degradation. For the case of embedded sensor networks it is not feasible to individually place sensors in random locations and orientations. Minimizing the perturbation to the host material requires that the optical fibers be embedded in a direction that is consistent with the local microstructure.[10] For this reason, we considered that the sensors were embedded in parallel, at a given optical-fiber orientation, and optimized the sensor spacing rather than the placement of individual sensors. As this significantly reduced the optimization problem to a single variable, heuristic methods were not required. The

method was applied to the specific case of a laminated composite plate with embedded FBG sensors subjected to low-velocity impacts. One hundred impact-loading cases were generated to calculate the probabilities of damage and detection. The applied impact loading was represented as a function of random variables, including both the magnitude and location of the impacts.

A flowchart of the sensor placement optimization method is shown in Figure 5(a). The results of these experiments were collected to form a lifetime damage model as a function of the number of embedded sensors. A second experimental-testing protocol was then established, this time to quantify the sensor response model (SRM) as a function of the laminate remaining lifetime and sensor locations. The resulting SRM included the spectral feature-extraction algorithms derived for the FBG sensor discussed previously and the fusion of data from multiple low-velocity-impact experiments. The SRM was applied through a receiver-operating-characteristic (ROC) analysis[11] and then combined with the lifetime damage model to generate an optimal sensor-spacing solution.
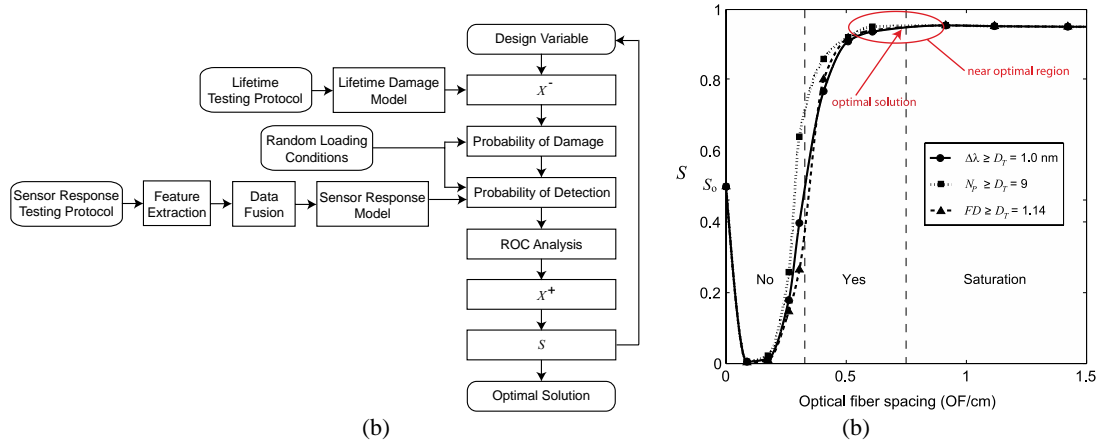

Figure 5. (a) Flowchart of optimization process for placement of embedded sensors. (b) Lifetime benefit function vs. optical-fiber spacing, plotted at a fixed detector threshold. Examples using three different sensor response models are plotted. S_0 is the value of the lifetime benefit function when no sensors are present.

The results of this sensor placement optimization demonstrated that the lifetime benefit function was an appropriate cost function for the optimization of embedded sensor placement for structural health monitoring of a composite airframe structure subjected to impact loading events. While this function was only demonstrated for a single example in this study, it is expected that similar behaviors would be observed for more complicated structural component geometries. As seen in Figure 5(b), the use of the lifetime benefit function was able to demonstrate regions of optical fiber spacings that yielded a negative effect, a positive benefit and a saturation value, beyond which the benefit did not significantly change. This behavior is *fundamentally different* than that observed when optimizing the sensor placement of surface mounted sensor networks, in which the presence of the sensors always yields a positive benefit. Low numbers of embedded optical fiber sensors create a negative effect on the total lifetime of a structural component, for which the replacement is governed by condition-based monitoring. The critical spacing value required to achieve an increase in component lifetime is a function of the component geometry and fabrication method, sensors and sensor feature extraction method applied, and expected loadings. The optimal sensor placement solution was not oversensitive to the particular sensor feature extraction method applied. The optimal solution was also extremely robust with respect to differences in the optical fiber spacing.

Electro-Thermal-Mechanical Modeling of Carbon Nanotube Polymer Composites

New finite element (FE) modeling methods and percolation techniques were developed to investigate how the electrical-mechanical-thermal behavior of carbon nanotube (CNT) reinforced polymer composites is affected by electron tunneling distances, volume fraction, and physically realistic tube aspect ratios. The percolation technique used a search algorithm and an electrical junction identification method to determine conductive paths for three dimensional (3D) carbon nanotube arrangements and to account for electron tunneling effects. The predicted results were used to understand the limitations of percolation theory and experimental measurements and observations, and why percolation theory breaks down for specific CNT arrangements. Representative CNT polymer composite conductive paths were then chosen from the percolation analyses to establish the three-dimensional (3D) computational finite-element (FE) approach.

A specialized Maxwell FE formulation with a Fermi-based tunneling resistance was then used to obtain current density evolution for different CNT/polymer dispersions and tunneling distances (see Figure 6). Analyses based on thermo-electrical and electro-thermo-mechanical FE approaches were used to understand how CNT-epoxy composites behave under electro-thermo-mechanical loading conditions. Scaling relations were developed to obtain gauge factors for different CNT arrangements within a polymer composite to ascertain piezo-resistive behavior for different CNT distributions and arrangements. The long-term impact of the work is that the validated computational approaches can result in optimal electro-mechanical sensing capabilities for CNTs with different aspect ratios, tunneling distances, and orientations. These simulation results will be applied to extend the damage identification methodologies based on measurements at multiple physical and temporal scales, discussed above, to in-situ damage identification in CNT reinforced polymer composites.
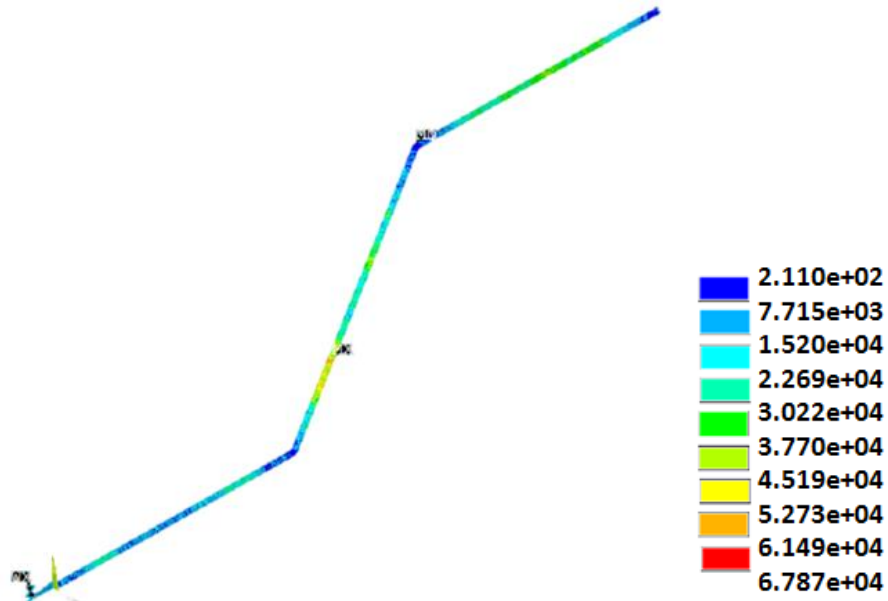

Figure 6. Normalized total current density for CNTs in epoxy matrix for a distribution of 1% CNTs within an epoxy matrix. The current density is normalized by the initial density and accounts for tunneling effects.

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	Adam Propst[*] (M.S. December 2008, Thesis Title: Damage Monitoring in Woven Composites using fiber-Bragg Grating Sensors on Multiple Time Scales[£])
	Siqi Xu (Ph.D. projected December 2012, Dissertation Title: Electro-thermo-Mechanical Microstructural Modeling of CNT Polymer Composites[£])

Publications resulting from project:

Journal Publications

1. R. Garret, K. Peters and M. A. Zikry (2009), "In-situ Impact-induced Damage Assessment of Woven Composite Laminates through a Fiber Bragg Grating Sensor Network," *Journal of the Royal Aeronautical Society* **113**:357-370.
2. S. Schultz, W. Kunzler, Z. Zhu, M. Wirthilin, R. Selfridge, A. Propst, M. A. Zikry, and K. Peters (2009), "Full-spectrum Interrogation of Fiber Bragg Grating Sensors for Dynamic Measurements in Composite Laminates," *Smart Materials and Structures* **18**:115015.
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7. C. Park and K. Peters (2012), "Optimization of Embedded Sensor Placement for Structural Health Monitoring of Composite Airframes," to appear in *AIAA Journal*.
8. C. Park and K. Peters (2012), "Comparison of Damage Measures based on Fiber Bragg Grating Spectra," *Measurement Science and Technology* **23**: 025105.
9. S. Xu, O. Rezvanian, K. Peters and M. Zikry (2012), "The Viability and Limits of Percolation Theory in Modeling the Electrical Behavior of Carbon Nanotube Polymer Composites," submitted to *Journal of Applied Physics*.
10. S. Xu, O. Rezvanian, K. Peters, M.A. Zikry(2012), "Electro-Thermal-Mechanical Modeling of Carbon Nanotube Polymer Composites," to be submitted.

Conference Proceedings Publications

1. R. Garret, J. Pearson, K. Peters and M. Zikry (2007), "Optimization of Fiber Bragg Sensor Configurations for In-Situ Failure Identification in Woven Composites throughout Impact," *SPIE Proceedings, Sensor and Smart Structures Technologies for Civil, Mechanical and Aerospace Systems, Smart Materials and Structures,* San Diego, CA, **6529**.
2. R. Garret, K. Peters and M. A. Zikry (2007), "Sensor Networks for In-Situ Failure Identification in Woven Composites throughout Impact," *Proceedings of the IMECE2007*, ASME, Seattle, WA.
3. A. Propst, A. Parker, Z. Capps, K. Peters and M. A. Zikry (2008), "Damage Monitoring in Woven Composites using Fiber-Bragg Grating Sensors on Multiple Time Scales," *ASME SMASIS Conference*, Baltimore, MD, paper # SMASIS08-527.

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Interactions/Transitions resulting from project:

- Micron Optics Inc. loaned the project the use of a research prototype peak wavelength interrogator (si920) currently in development. This interrogator was used to measure the response of the fiber Bragg grating sensors to combine peak wavelength scanning with the full-spectral sweeps. We were therefore able to quantitatively compare different strategies to capturing sensor information at high speeds and correlate this sensor information to damage states within the composite laminates.

- The project investigators developed a collaboration with researchers in the Department of Electrical and Computer Engineering at Brigham Young University during the project. As a result we designed, implemented and tested a full-spectral interrogator for fiber Bragg grating sensors that performed full-spectral sweeps at rates up to 1 kHz. This interrogator was later further developed to increase the full-spectral sweep rate to 100 kHz through separate funding obtained from the National Science Foundation.